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EFFECTS OF INTERMEDIATE CHANNELS IN ISOSPIN FORBIDDEN REACTIONS

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It is shown that intermediate channels can significantly contribute to isospin forbidden reactions The properties of the apparent violation are discussed and experiments suggested to test the validity of the assumptions The contributions of intermediate stripping channels to the $^{12}C(d,d')^{12}C^*$ ($T=1$) reaction is estimated

Recently, evidence has been presented [1] for a large isospin violation in two direct reactions with deuterons as projectiles. Because the observed effect is much larger than that which can arise due to the Coulomb force, it has been argued that it gives evidence for the existence of a isospin violating component in the nuclear force

In this letter we want to point out that a large violation seen in a direct reaction does not necessarily imply a large violation in the nucleon-nucleon force. In fact, intermediate channels other than the direct entrance and exit channels, can significantly contribute to the forbidden cross-section, and thus give rise to an apparent violation in the *effective* interaction responsible for the scattering.

To make this point clear we consider the relatively simple $^{12}C(d,d')^{12}C^*$ reaction leading to the 15.11 MeV, 1^+ $T=1$ state in ^{12}C, discussed in ref. [1]. As intermediate channels we consider the stripping channels $^{13}C + p$ and $^{13}N + n$ and introduce a coupled channel description of the scattering process, with four channels 1) the elastic entrance channel $d + {}^{12}C$, $T=0$; 2) the stripping channel $^{13}C + p$, 3) the stripping channel $^{13}N + n$; 4) the isospin forbidden exit channel $d + {}^{12}C^*$, $T=1$. The scattering process is then described by a system of four coupled equations

$$E\psi_1 = H_{01}\psi_1 + V_{11}\psi_1 + V_{12}\psi_2 + V_{13}\psi_3, \qquad E\psi_2 = H_{02}\psi_2 + V_{21}\psi_1 + V_{24}\psi_4, \tag{1}$$

$$E\psi_3 = H_{03}\psi_3 + V_{31}\psi_1 + V_{34}\psi_4, \qquad E\psi_4 = H_{04}\psi_4 + V_{42}\psi_1 + V_{43}\psi_3 + V_{44}\psi_4,$$

where the coupling between channels 1 and 4 is explicitly set to zero, i e $V_{41} = V_{14} = 0$, because of the isospin forbiddeness. We also set $V_{22} = V_{23} = V_{32} = V_{33} = 0$ since we are not interested in the details of the scattering in channels 2 and 3 but only in the effects of these two channels on the isospin forbidden reaction.

Following Feshbach [2] we can eliminate channels 2 and 3 from the system, eq. (1), by introducing the Green function of the operators $(E - H_{02})$ and $(E - H_{03})$

$$G_2^{(+)} = \lim_{\epsilon\to 0^+} \frac{1}{E - H_{02} + i\epsilon}, \qquad G_3^{(+)} = \lim_{\epsilon\to 0^+} \frac{1}{E - H_{03} + i\epsilon} \tag{2}$$

with the result

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$$E\,\psi_1 = H_{01}\psi_1 + [V_{11} + V_{12}G_2^{(+)}V_{21} + V_{13}G_3^{(+)}V_{31}]\,\psi_1 + [V_{12}G_2^{(+)}V_{24} + V_{13}G_3^{(+)}V_{34}]\,\psi_4 \tag{3}$$

$$E\,\psi_4 = H_{04}\psi_4 + [V_{42}G_2^{(+)}V_{21} + V_{43}G_3^{(+)}V_{31}]\,\psi_1 + [V_{44} + V_{42}G_2^{+}V_{24} + V_{43}G_3^{(+)}V_{34}]\,\psi_4$$

Eq. (3) shows that the effect of the intermediate channels 2 and 3 can be represented by a potential

$$V_{\text{eff}} = V_{12}G_2^{(+)}V_{24} + V_{13}G_3^{(+)}V_{34}, \tag{4}$$

which effectively couples channels 1 and 4. This expression can be rewritten in a different form in order to display explicitly its isospin violation. To this end let us introduce the isospin wave functions of ^{13}C + p and ^{13}N + n, denoted hereby $|+-\rangle$ and $|-+\rangle$ respectively. These wave function can be decoupled into their isospin zero and one parts

$$|+-\rangle = \sqrt{\tfrac{1}{2}}\,|1\;0\rangle + \sqrt{\tfrac{1}{2}}\,|0\;0\rangle, \qquad |-+\rangle = \sqrt{\tfrac{1}{2}}\,|1\;0\rangle - \sqrt{\tfrac{1}{2}}\,|0\;0\rangle. \tag{5}$$

Assuming all interactions to be isospin conserving we can write

$$V_{12} = \langle\chi_1\;T{=}0|V|\chi_2\rangle = \langle\chi_1|V|+-\rangle = \sqrt{\tfrac{1}{2}}\langle\chi_1|V|0\;0\rangle \equiv \sqrt{\tfrac{1}{2}}\,V_\alpha, \tag{6}$$

$$V_{13} = \langle\chi_1\;T{=}0|V|\chi_3\rangle = \langle\chi_1|V|-+\rangle = -\sqrt{\tfrac{1}{2}}\langle\chi_1|V|0\;0\rangle \equiv -\sqrt{\tfrac{1}{2}}\,V_\alpha,$$

$$V_{24} = \langle\chi_2|V|\chi_4\;T{=}1\rangle = \langle+-|V|\chi_4\rangle = \sqrt{\tfrac{1}{2}}\langle1\;0|V|\chi_4\rangle \equiv \sqrt{\tfrac{1}{2}}\,V_\beta, \tag{7}$$

$$V_{34} = \langle\chi_3|V|\chi_4\;T{=}1\rangle = \langle-+|V|\chi_4\rangle = \sqrt{\tfrac{1}{2}}\langle1\;0|V|\chi_4\rangle = \sqrt{\tfrac{1}{2}}\,V_\beta.$$

where use has been made of the T=0 nature of the entrance channel isospin wave function χ_1 and of the T=1 nature of the exit channel isospin wave function χ_4. Thus eq. (4) can be rewritten as

$$V_{\text{eff}} = \tfrac{1}{2}\,(V_\alpha G_2^{(+)} V_\beta - V_\alpha G_3^{(+)} V_\beta). \tag{8}$$

If channels 2 and 3 were exactly identical then $G_2^{(+)} = G_3^{(+)}$ and $V_{\text{eff}} = 0$. However, Coulomb energy shifts and related effects make channels 2 and 3 slightly different thus introducing an *apparent isospin violation* in the scattering process $1 \to 4$.

In discussing the properties of the effective potential V_{eff} we first note that in principle all states in ^{13}C and ^{13}N can contribute to the isospin forbidden reaction. In practice only those states which have a large overlap with both the entrance and exit channels need be considered. If only one (or few) intermediate states contribute to eq. (8), the effective potential will be strongly energy dependent having its maximum value around the threshold energy for channels 2 and 3. On the other side if many closely spaced states contribute to eq. (8), the effective potential will be only slowly energy dependent. V_{eff} is obviously also process dependent. The apparent violation due to intermediate channels appears therefore differently in different reaction, in contrast to an intrinsic violation which appears equally well in all reactions. Finally the angular distribution for the scattering through intermediate channels is presumably flatter than that of the direct scattering. Therefore the apparent violation expressed as ratio of the isospin forbidden to the isospin allowed cross-section, corrected for the Q-value variation, should also depend on the scattering angle.

Since a realistic solution of the coupled-channel equation is hardly possible we suggest that these criteria should be used to judge whether the violation reported in ref. [1] is intrinsic or not. In particular other reactions leading to the same 15.11 MeV, 1^+ T=1 state in ^{12}C should be studied and the energy and angle dependence of the violation carefully analyzed.

In order to estimate the expected order of magnitude of the apparent violation we have solved the coupled channel equations eq. (1) using surface delta functions as coupling potentials. The contribution of the $\frac{3}{2}^-$, T=$\frac{1}{2}$ state, which appears in ^{13}C at 3.68 MeV and in ^{13}N at 3.51 MeV, to the isospin forbidden reaction has been found to be of the order of 0 5 – 1.0% of the isospin allowed reaction, a value consistent with the experimental result of ref. [1]. Of the four low-lying states of $^{13}C(^{13}N)$ below 3.8 MeV the $\frac{3}{2}^-$ state is the only one having appreciable overlap (~ 0.2) with both the entrace and exit channels. Surface delta functions have been used because for these potentials the coupled channel system resolves to a system of algebraic equations which can be solved analytically [3]. The strengths and radii of the surface delta forces have been fixed by fitting the elastic $^{12}C(d,d)^{12}C$ and stripping $^{12}C(d,p)^{13}C(3.68)$ experimental cross sections [4, 5]. A modification of the surface delta to take into account the L=1 transferred angular momentum in the stripping reaction has been used following the work of Rawitscher [6].

From the considerations above and until more detailed experimental investigations are performed, it appears to us that any conclusion about isospin violation in the nuclear forces is premature.

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